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Laboratory Methods for Measuring Battery Resistance

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LABORATORY METHODS FOR MEASURING BATTERY RESISTANCE

BY

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THESIS

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THIS IS TO CERTIFY THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

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ENTITLED LABORATORY METHODS FOR MEASURING BATTERY RESISTANCE

IS APPROVED BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

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INTRODUCTION

Experiments on the measurement of the internal resistance of a battery are, for the most part, very unsatisfactory. In the first place it is almost impossible to get consistent results because of the fact that the resistance of the cell changes, quite rapidly sometimes. Again, it is impossible to measure the resistance of a conductor without passing some current through it, and,in the case of a cell, it is found that the resistance varies (inversely) with the current, so to get consistent results the resistance must be measured under the same conditions each time. Another difficulty is that some cells polarize quite rapidly when giving out a current. This changes the resistance. In the case of a liquid cell the resistance may be very materially altered by stirring up the liquid. This is especially true of a gravity cell.

Having some of these difficulties in mind it was the purpose of the writer to investigate some of the methods and to determine which are best adapted for use in the laboratory.

Since dry cells, gravity cells, and storage cells are the ones in general use in laboratories the investigations will be confined to these.

METHODS INVESTIGATED

The first investigated is a method by Carhart and

Patterson* in which the arrangement of apparatus is as shown in the accompanying diagram.

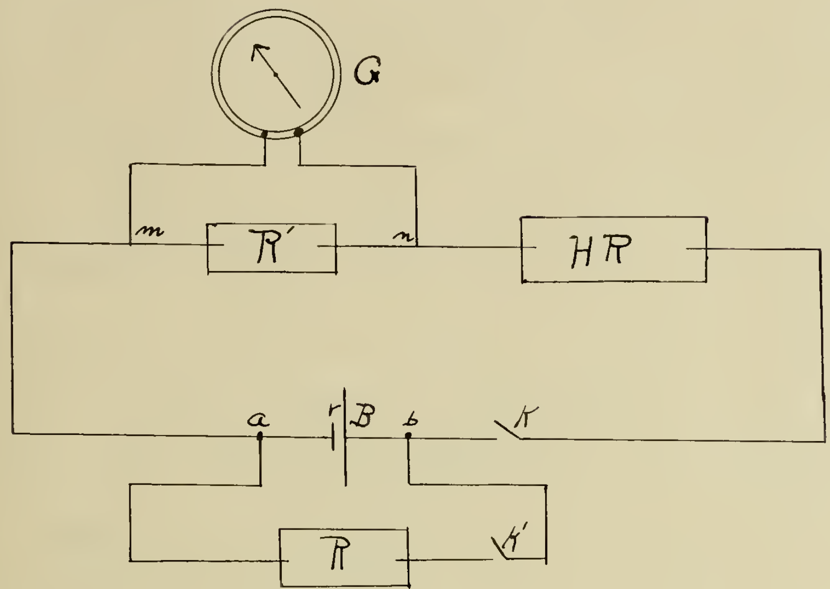

Fig. I.

HR is a high resistance, and R' is a resistance whose magnitude depends upon the resistance in HR, upon the E.M.F. of the cell, and upon the sensitivity of the galvanometer. Neither of these resistances need be known, but they must remain constant throughout the experiment. B is the battery whose resistance, r, is to be determined. R is a variable resistance whose value is usually small (approximately equal to that of r) and which must be accurately known. K and K' are keys. K should be a plug or mercury key, while K' should be a tapping key. G is a galvanometer.

With the above arrangement K is closed, K' being open, and a reading, d, of the galvanometer is taken. This,

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* Carhart and Patterson. Electrical Measurements p 98

of course, is a steady deflection which should be, in the case of a Nalder or Leeds and Northrup Type H galvanometer, from 100 to 150 mm. K' is then closed, having R equal approximately to r, and a second reading, d" is taken.

Since R' is unchanged throughout the experiment the current through G, and consequently the deflection, d, is directly proportional to the difference of potential between the points m and n, and since HR is unchanged the difference of potential between m and n is directly proportional to that between the terminals, a and b, of the battery. Let E be the difference of potential between a and b when K is closed and K' open, and E' the difference of potential between the same points when both K and K' are closed. Then from the above we have; d' : d" :: E : E' Since HR is high, say 10000 ohms, and in most cases r is small, say 5 ohms, we can say that E is the total E.M.F. of the cell. This, of course, is neglecting 5 points in 10000 or about 1/20 of 1 per cent. This is less than the experimental error. In the other case, however, viz., when K and K' are both closed, the resistance between a and b can never be greater than that in the smaller of the parallel resistances, viz., R. In this case if we neglect r it is neglecting 5 in R + 5 or, if R = 10, it is neglecting 5 in 15 or 33-1/3 per cent. Since, by Ohm's law, the fall of potential in a circuit is directly proportional to the resistance, and using the same values for r and R we have 1/3 of the fall of potential taking place inside the battery and 2/3 outside, or in gen-

$\frac{r}{R+r}$ of the fall of potential takes place inside the battery and $\frac{R}{R+r}$ outside. Then $E' = \frac{R}{R+r} E$. Now we may write from the above equation:

$$d' ; d'' :: E : \frac{R}{R+r} E \quad \text{or} \quad d' : d'' :: (R+r)E : RE,$$

$$\text{or} \quad d' : d'' :: R+r : R, \text{ or } d' - d'' : d'' :: r : R.$$

whence,
$$r = R\,\frac{d' - d''}{d''}.$$

With the above arrangement the following data were taken for the resistance of a gravity cell:

Blue Cell No. 2				Galvanometer as Ammeter			
d' mm.	d" mm.	R ohms	r ohms	d' mm.	d" mm.	R ohms	r ohms
176	116	10	5.17	183.5	134.5	15	5.46
178	117	10	5;21	185.5	135.5	15	5.53
179	117.5	10	5.24	185	135	15	5.55
180	118	10	5.25	185	135	15	5.55
181	118.5	10	5.27	185	134.5	15	5.63

It may be seen from the above data that so long as R is constant fairly consistent results are obtained. On the other hand we see that when R is changed the value of r is changed. This suggested a slight modification in the experiment. In order to prevent such rapid chemical action inside the cell as had previously occurred I placed a resistance, P, in series with the battery and then measured P + r as I had previously measured r. Following are the results:

Blue Cell No I. Galvanometer as ammeter

d'mm	d"mm	P ohms	R ohms	r ohms	d'mm	d"mm	P ohms	R ohms	r ohms
95	45.5	10	12	3.05	99.5	48	14	16	3.17
126	62.5	10	13	3.20	96.5	47	15	17	2.89
126	76	10	20	3.16	96	51	15	20	2.65
125.5	76	10	20	3.03	95.5	34.5	15	10	2.68
126	76	10	20	3.16	96	29.5	20	10	2.54

The above results are seen to be very inconsistent and unreliable. The previous arrangement is much better.

The same method was applied to the determination of the resistance of a dry cell. The following table shows the results:

Dry Cell Galvanometer as ammeter

d'mm	d"mm	P ohms	R ohms	r ohms	d'mm	d"mm	P ohms	R ohms	r ohms
181	132	0	4	1.48	165.5	96.5	10	20	4.32
163	109	0	4	1.98	164.5	96.5	10	20	4.09
160	100.5	0	4	2.37	164.	141.	0	20	3.26
164.5	71	10	10	3.17	169.	140.	0	20	4.14
163	84.7	10	15	3.87	171.	85.5	15	20	3.21

The above shows that this method either with or without P is unreliable for the measurement of a dry cell. Too long a time is taken to get a reading and the cell is subject to polarization during that time.

A modification of the above method* was next employed. The theory and formula are the same, but the arrangement of

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* Carhart and Patterson. Electrical Measurements p 100

apparatus is somewhat different. A sketch of the set up is given in Fig. 2.

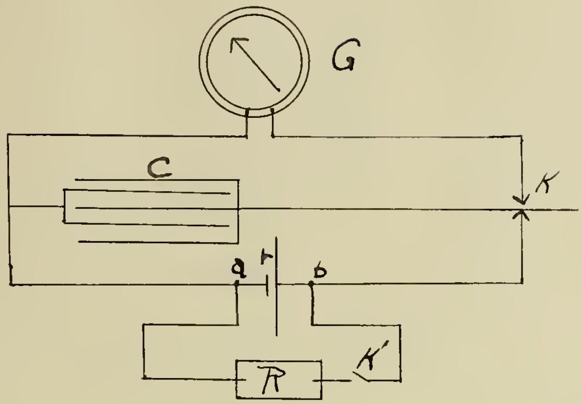

Fig. 2

In this method a condenser is charged and discharged by means of the Kemp key, K. In the first place it is charged with the full E.M.F., E, of the cell, and secondly with the potential difference, E', between the terminals, a and b, of the cell when K' is closed. This has the advantage over the previous method of necessitating K' to be closed only just long enough to allow for the charge and discharge of the condenser through K.

Following is a set of data taken by this method:

Dry Cell No. I				Condenser Method			
d' mm	d" mm	R ohms	r ohms	d' mm	d" mm	R ohms	r ohms
249	210	10	1.86	237	209	30	4.02
245	205	10	1.95	236	207	25	3.50
244	204	10	1.96	236	205	20	3.02
246	203	10	2.12	237	202	15	2.60
240	200	10	2.00	237	198	12	2.36
234	195	10	2.00	233	192	10	2.13
237	197	10	2.03	232	186	8	1.97
234	195	10	2.00	235	177	5	1.64
233	197	10	1.83	235	140	3	2.03
232	196	10	1.84	235	138	3	2.07

In the first half of the data we see that there is a great deal more consistency in this method for the dry cell than in the previous method. This is not very satisfactory, however, as it may be seen by taking the maximum and minimum results that there is a variation of about 15 per cent. Some of this may be accounted for by errors in reading the deflection. This, of course, is a ballistic throw and if the period of the galvanometer is short it is quite difficult to read the throw accurately. Take, for example, the first set of readings. Suppose the correct reading of d' had been 250 instead of 249, and that of d" 209 instead of 210. Then r would have been 1.96 ohms instead of 1.86 ohms. An error of 1mm. might easily be made in any of these readings, and so a great deal of the variation may be due to that. If, then, this method is used great care should be taken in reading the deflection, and if possible a long period galvanometer should be used.

The second half of the above data shows what has been mentioned before, viz., that the resistance of the cell varies inversely as the current or directly as the external resistance. The last two readings, however, seem to offer evidence to the contrary, but I think this rise in resistance may be explained by the fact that the cell polarized when short-circuited through a three ohm resistance even though the time was very short.

The condenser method was also used with the blue cell. The results are shown below:

Blue Cell Condenser Method---

				Resistance, P, added to battery				
d'mm	d"mm	R ohms	r ohms	d'mm	d"mm	P ohms	R ohms	r ohms
147.0	116.0	10	2.67	143.0	117.0	0	13	2.89
147.5	119.0	11	2.64	141.8	124.5	0	20	2.85
147.0	120.0	12	2.70	144.5	126.5	0	30	2.85
147.	121.5	13	2.73	142.0	62.0	10	10	2.90
148.	125.0	15	2.72	143.0	72.0	10	13	2.82

The above table shows that this method is well adapted to the measurement of the resistance of a blue cell. The addition of the resistance in series with the cell seems to have little effect upon the results.

Another method used is Mance's Method.* In this a Wheatstone's bridge arrangement is used where the battery to be measured is placed in one arm of the bridge. The diagram of apparatus is shown in the accompanying figure.

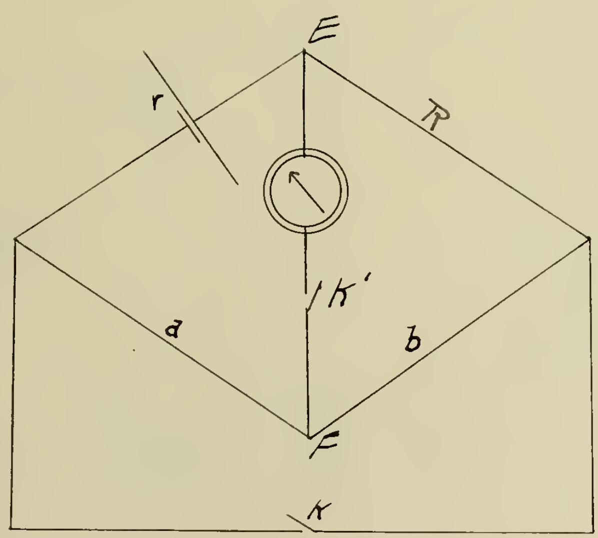

Fig. 3.

*Nichols. Laboratory Manual of Physics and Applied Electricity. p. 217. Watson. Practical Physics. p. 475.

Theory:- In this experiment the thing to be done is to close K' and get a steady deflection, and then so adjust a, b, and R that when K is closed there is no change in the steady deflection, or in other words the current through the galvanometer is unchanged. If we let I' be the current flowing when K is open and K' closed, and I'_g the current through the galvanometer at the same time, I" and I''_g the corresponding currents when K and K' are both closed we have: Case I.

K open, K' closed.

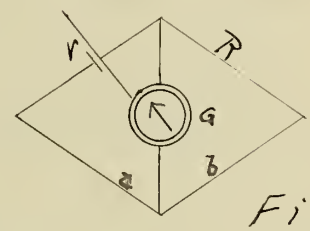

Fig. 4.

$$I' = \frac{e}{r + a + \frac{G(R+b)}{G+R+b}}$$

$$I'_g = I'\left(\frac{R+b}{R+b+G}\right) = \frac{e}{r + a + \frac{G(R+b)}{G+R+b}} \cdot \frac{R+b}{G+R+b}$$

Case II.

K and K' both closed.

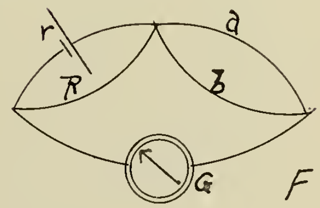

Fig. 5.

$$I'' = \frac{e}{r + \frac{R\left(\frac{ab}{a+b}+G\right)}{R+\frac{ab}{a+b}+G}}$$

$$I''_g = I''\frac{R}{R+\frac{ab}{a+b}+G} = \frac{e}{r+\frac{R\left(\frac{ab}{a+b}+G\right)}{R+\frac{ab}{a+b}+G}} \cdot \frac{R}{R+\frac{ab}{a+b}+G}$$

Since the deflection is the same for the two cases we have:

$$I_g' = I_g''$$

Substituting the values found above for I_g' and I_g'' and simplifying we have:

$$br = aR \quad \text{or} \quad \frac{r}{R} = \frac{a}{b}$$

If the resistances a and b constitute the meter wire of the Wheatstone's bridge only we may write

$$(1) \quad \frac{r}{R} = \frac{a'}{1000 - a'}$$ where a' is

the length in mm. of the part of the bridge wire whose resistance is a, and $1000 - a'$ is the length in mm. of the part whose resistance is b.

A commutator bridge was used. By commutating, or, in fact, interchanging r and R we have

$$(2) \quad \frac{r}{R} = \frac{1000 - a''}{a''}$$

Now adding equations (1) and (2) by addition of numerators and denominators we have

$$\frac{r}{R} = \frac{1000 + (a' - a'')}{1000 - (a' - a'')}$$

which is the equation that I used.

The above arrangement was found to involve several difficulties. First, whenever the sliding contact along a b was to be changed it was necessary to break the galvanometer circuit in order to prevent injury to the bridge wire by scratching. This, of course, threw the steady balance off, then after closing the galvanometer key it was necessary to wait for the galvanometer to come to rest again. This, in case of a cell that is subject to polarization, renders the method impracticable. In order to overcome

this difficulty a slightly different arrangement of apparatus was used. The set up is shown below:

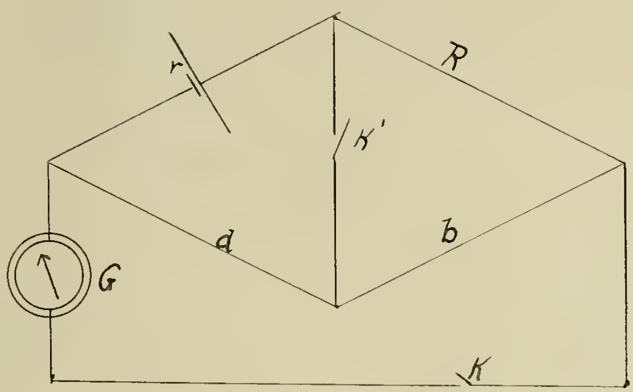

Fig. 6.

This, it will be seen, involves simply the interchanging of the galvanometer circuit and the wire which formerly occupied the position of the battery in the ordinary Wheatstone's bridge arrangement.

For this arrangement the operation is the same as before, viz., close K and obtain a steady deflection and then so adjust the resistances R, a, and b that when K' is closed there is no change in deflection of the galvanometer, or, in other words, the current through the galvanometer is unchanged by the closing of K'.

Case I. K closed, K' open.

$$I' = \frac{e}{r + R + \frac{G(a+b)}{G+a+b}}$$

$$I_g' = I' \frac{a+b}{G+a+b} = \frac{e}{r+R+\frac{G(a+b)}{G+a+b}} \cdot \frac{a+b}{G+a+b}$$

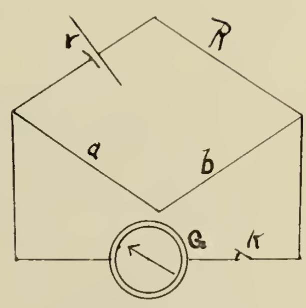

Fig. 7.

I = total current. I_g = current through the galvanometer.

$$I' = \frac{e(a+b)}{rG + ra + rb + RG + Ra + Rb + Ga + Gb}$$

Case II. K and K' both closed.

$$I'' = \frac{e}{r + \dfrac{a\left(\dfrac{bR}{b+R} + G\right)}{a + \dfrac{bR}{b+R} + G}}$$

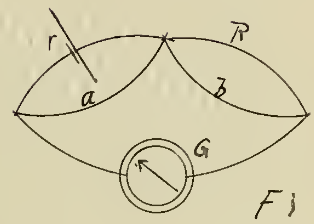

Fig. 8.

$$I_g'' = I'' \frac{a}{a + \dfrac{bR}{b+R} + G} = \frac{e}{r + \dfrac{a\left(\dfrac{bR}{b+R} + G\right)}{a + \dfrac{bR}{b+R} + G}} \cdot \frac{a}{a + \dfrac{bR}{b+R} + G}$$

$$I_g'' = \frac{ea}{ra + \dfrac{rbR}{b+R} + rG + \dfrac{abR}{b+R} + aG}$$

$$I'' = \frac{ea(b + r)}{rab + raR + rbR + rbG + rRG + abR + aGb + aGR}$$

Then since the current through the galvanometer is unchanged

I' = I" or

$$\frac{(a+b)}{rG + ra + rb + RG + Ra + Rb + Ga + Gb}$$

$$= \frac{a(b + R)}{rab + raR + rbR + rbG + rRG + abR + aGb + aGR}$$

clearing of fractions and simplifying we have

$$aR^2 G + a^2 R^2 + aR^2 b + aRGb = abrR + b^2 rR + b^2 rG + brRG$$

aR = br which reduces to $\frac{r}{R} = \frac{a}{b}$ and is the same as derived for the previous arrangement. In this case the commutator was also used and the equation for that part is developed exactly as before. The final form which was used is:

$$r = R\frac{1000+(a'-a'')}{1000-(a'-a'')}$$

This arrangement was found to be not only very much more convenient to work with as indicated above, but was also much more sensitive. The method was found to be fairly satisfactory for blue cells, but in case of dry cells the time necessary to keep the circuit closed was long so that the cell polarized and no consistent results could be obtained. Below is shown a series of data taken on a blue cell:

Mance's Method Blue Cell No.I				Same cell four days later.			
a'mm	a"mm	R ohms	r ohms	a'mm	a"mm	R ohms	r ohms
272	743	8	2.88	277	733	8	2.92
242	762	9	2.84	252	757	9	2.96
223	780	10	2.85	238	765	10	3.09
206	803	11	2.78	224	786	11	3.09
197	814	12	2.84	210	794	12	3.15

It will be seen that the second set of data gives a higher value of r than the first, and also that the results are less consistent. This I think may be due to the fact that the cell had been standing on open circuit for several days. This would have a tendency to increase the resistance and also [have a tendency to increase the resistance and also] to

make the cell less constant.

Another objection to Mance's Method is the fact that the steady current through the galvanometer produces a large deflection and so renders the galvanometer less sensitive to small changes of current. It has been suggested that this objection may be overcome by adjusting the galvanometer so that the coil hangs in the most sensitive position when the current is flowing. This might be brought about by different methods. One plan that has been suggested is to turn the torsion head of the suspension sufficiently to bring about the desired result, another which applies in the case of a magnetic needle galvanometer is to control the deflection by means of an external magnetic field. Still another way of overcoming the difficulty was suggested by Lodge*. His plan was to place a condenser in series with the galvanometer. This served a double purpose. First, it reduced the permanent deflection to zero and, secondly, it protected the galvanometer from large currents. This plan was tried. Here again the question arose as to which of the two set ups of Mance's Method was more desirable. The first arrangement is shown below:

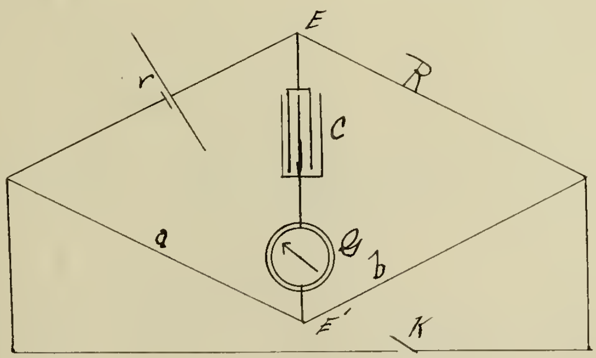

Fig. 9.

* Watson. Practical Physics, p. 476

In this case since there is a condenser in series with the galvanometer there is no steady current. The object then is to so adjust the resistances R, a, and b that when K is closed there will be no charge flow into or out of the condenser. This means that the difference of potential between E and E' is unchanged by opening or closing K.

Let e = E.M.F. of cell, I = total current,

I_g = current through the galvanometer.

Case I. K open.

$I = \dfrac{e}{r+R+a+b}$ and the difference of potential between E and E' which I will represent by E - E' is given by,

$$E - E' = I(r+a) = \frac{e(r+a)}{r+R+a+b}$$

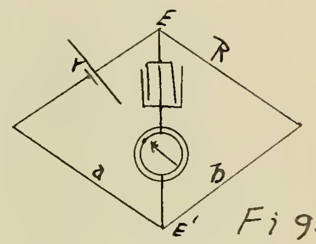

Fig.10.

Case II, K closed

$I = \dfrac{e}{r+R}$ since no current flows through the galvanometer circuit. For the same reason E''' and F are at the same potential.

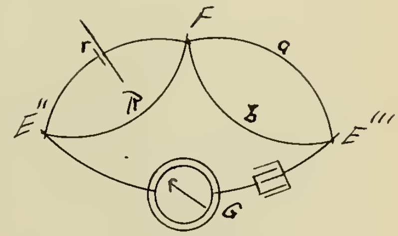

Fig.11.

Then

$$E'' - E''' = I'r = \frac{er}{r+R}$$

But the difference of potential between the points E and E' is unchanged:

Therefore $E - E' = E'' - E'''$ or

$$\frac{e\,(r + a)}{r + R + a + b} = \frac{e\,r}{r + R}$$ clearing of fractions we

have:

$$rb = Ra$$

Then $rb = Ra$ or $\frac{r}{R} = \frac{a}{b}$ This formula is identical with that of the other form of Mance's Method and so the formula for the commutator type of bridge may be developed in exactly the same way as before. The formula then is identical with that of the other method, viz.,

$$r = R\,\frac{1000 + (a' - a'')}{1000 - (a' - a'')}$$

This set up was tried but with very little success. The arrangement was not very sensitive. The other arrangement was then tried. The set up is as shown below:

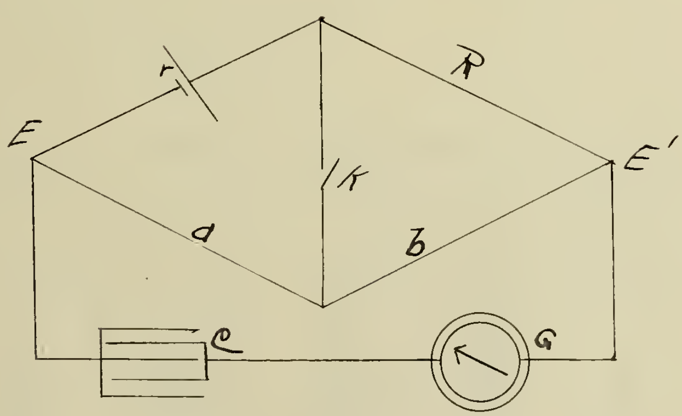

Fig. 12.

The conditions to be fulfilled are exactly the same as before, viz., that the difference of potential between E and E' is unchanged by closing K.

Case I. K open.

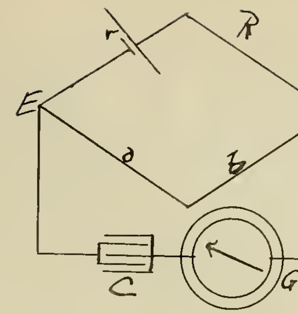

Fig. 13.

$$I = \frac{e}{r + R + a + b}$$

$$E - E' = I(R + r) = \frac{e(R + r)}{r + R + a + b}$$

Case II. K closed.

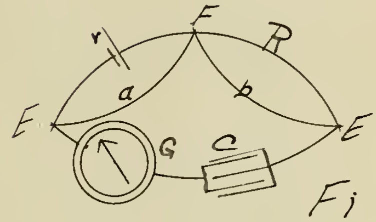

Fig. 14.

$I' = \dfrac{e}{r + a}$ and $E'' - E''' = I'r$

or $E'' - E''' = \dfrac{er}{r + a}$ and since

$E - E'$ is unchanged we have

$$E - E' = E'' - E''' = \frac{e(R + r)}{r + R + a + b} = \frac{er}{r + a}$$

clearing and reducing we have:

$$rb = aR \quad \text{or} \quad \frac{r}{R} = \frac{a}{b}$$

Here again the same formula as before applies. The results of this method are shown below:

Lodge's Modification

Blue Cell No. I				Same cell four days later.			
a'mm	a"mm	R ohms	r ohms	a'mm	a"mm	R ohms	r ohms
218	775	8	2.28	237	765	8	2.47
184	816	10	2.26	209	779	9	2.40
160	839	12	2.29	205	798	10	2.56
169	827	11	2.27	187	816	11	2.50
200	798	9	2.27	175	824	12	2.56

The second set of data shows the same effect as in Mance's original method on a previous page, viz., that the standing

of the cell caused the resistance to increase and also to be less constant. The results of this method are seen to be more consistent than in Mance's original method. This method was also tried on a dry cell, but as before too long a time was required to obtain a balance and so the cell polarized, and the data was very unsatisfactory.

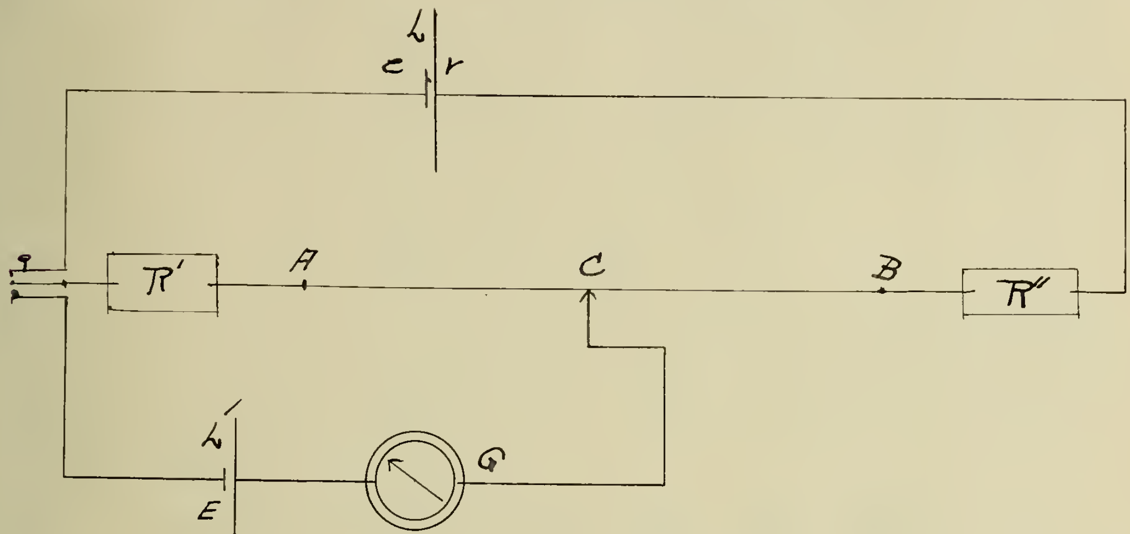

Fig. 15.

The above arrangement is one suggested by Beetz*. This method, they claim, has the advantage of necessitating the battery circuit to be closed only a very short time, and thus polarization is avoided to a large extent. Let L be the cell whose resistance, r, is to be measured. Its E.M.F. is e. L' is an auxiliary cell whose E.M.F., E, is less than e. R' and R" are resistance boxes, and AB is a slide wire of a Wheatstone's bridge. K is a three way key.

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* D. C. Miller. Laboratory Physics, p. 307

Watson. Practical Physics, p. 476

Let a = the total resistance between A and B.

b = " " " " A " C

$m = R' + R'' + a$

$n = R' + b$

Then $I = \frac{e}{r + m}$ where I is the current in upper branch.

Since no current flows through the galvanometer the total E.M.F., E, of the auxiliary cell is impressed on the circuit between K and C, but the current I just balances this so we have:

$$I = \frac{e}{r+m} = \frac{E}{n} \quad \text{or} \quad \frac{e}{E} = \frac{r+m}{n}$$

Now readjust R', R", and b for another balance and let the corresponding quantities be represented by R"', R"", a', m', and n'.

Then in analogy to the previous case $\frac{e}{E} = \frac{r+m'}{n'}$

Now since $\frac{e}{E}$ is unchanged we have,

$$\frac{r+m}{n} = \frac{r+m'}{n'}.$$ Solving for r we have,

$$r = \frac{mn' - m'n}{n - n'}$$ or substituting in the original values we have,

$$r = \frac{(R'+R''+a)\,(R'''+a') - (R'''+R''''+a')\,(R'+a)}{(R'+a) - (R'''+a')}$$

Using this method I measured the resistance of a storage cell having the safety coil in it. This coil was 1.68 ohms. For an auxiliary cell a blue cell was used. Following are the results:

Beetz's Method. Storage cell with 1.68 ohm coil in series.

---Blue cell as auxiliary

R' ohms	R" ohms	a ohms	R"' ohms	R""ohms	a' ohms	r ohms
22	31	.54	25	35	.38	1.919
30	42	.26	35	49	.14	1.77
33	46	.10	27	38	.43	2.09
24	34	.40	22	31	.38	1.76
21	29	.29	23	32	.32	1.80

Beetz's Method. Storage cell with shunted storage cell

for auxiliary

R' ohms	R" ohms	a ohms	R"' ohms	R"" ohms	a' ohms	r ohms
20	29	.4838	25	36	.270	1.72
30	44	.4727	27	39	.2681	1.64
23	33	.2867	26	38	.4678	1.68
29	42	.2636	24	34	.0700	1.61
22	32	.4800	28	41	.4690	1.59

The second set of data is seen to be much more consistent than the first. This is due to the more steady auxiliary cell.

I tried the same method for a dry battery, but found that the method was so sensitive that it was almost impossible to get a balance. I found that a difference of a fractional part of a second in the time of holding the key closed was sufficient to cause a variation in the readings, due to polarization. For just a tap of the key the galvanometer would deflect first in one direction and then in the other. If I attempted to hold the key closed for just a short time the deflection would go first in one direction and then within less than five seconds it would go clear off the scale in the other direction. Sometimes then it

would take a change of resistance of two ohms in R' or R" to bring it back onto the scale. The cell being short circuited through a low resistance polarized so rapidly that no consistent results could be obtained.

The next method taken up was one for determining the resistance of a cell or series of cells whose resistance is very small. In this case I used storage cells*. The arrangement of apparatus is shown in Fig. 16.

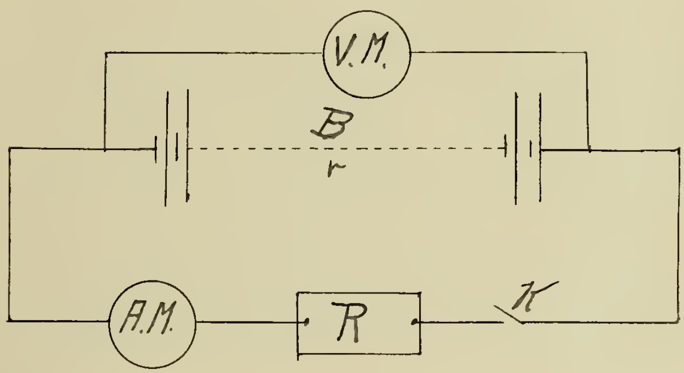

Fig. 16.

Let B be the battery, VM a voltmeter, AM an ammeter, R a resistance which need not be known, K a key. Let r = the resistance of the cells to be measured.

With K open read the voltmeter. Let this reading be E. Then close K and quickly read both AM and VM. Let the AM reading be I and the VM reading E'. Then from Ohm's Law $E = E' + rI$ where rI is the fall of potential through the cells due to the resistance r. For a more

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* Carhart and Patterson. Electrical Measurements. p 96.

convenient form we may write

$$r = \frac{E - E'}{I}$$

Following is a series of data taken:

50 Storage cells in series. Discharging.

E volts	E'volts	I amp	r ohms	E volts	E'volts	I amp	r ohms
103.8	101	1.23	2.28	103.8	101	1.225	2.29
103.9	101.1	1.23	2.28	103.8	101.1	1.23	2.19
103.8	101.1	1.23	2.19				
103.8	101.1	1.23	2.19				
103.8	101.	1.225	2.29				

In this case errors of reading the voltmeter and ammeter may account for all of the variation. In the numerator we have the ammeter reading and the difference of the VM readings. This latter is a very probable source of error since a very small error in either reading might be a large per cent of the difference.

This same principle may also be used to determine the resistance of the storage cells on charging.

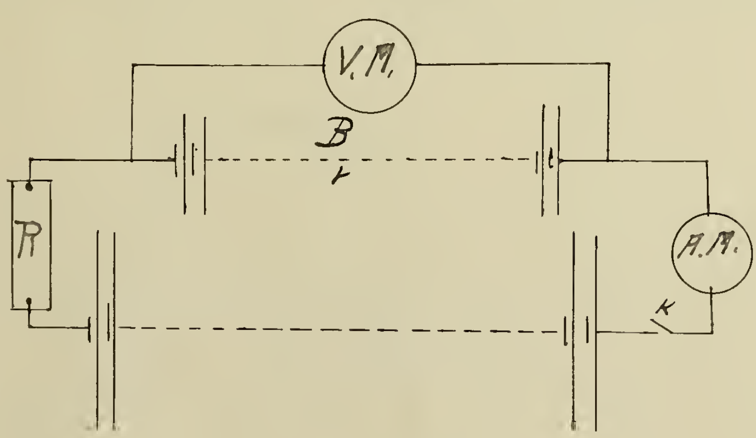

Fig. 17.

The readings are made just as before.

Let E = difference of potential on open circuit
E' = " " " during charging
I = current.

Then as before $E' = E + Ir$ or $\frac{E' - E}{I} = r$

Following is the data:

50 storage cells in series. Charging.

E'volts	E volts	I amp	r ohms	E'volts	E volts	I amp	r ohms
114.5	111	1.23	2.84	114.3	111.5	1.15	2.43
114.6	111.6	1.25	2.40	114.2	111.4	1.18	2.38
114.7	111.7	1.15	3.61	114.3	111.8	1.13	2.21
114.7	111.8	1.25	2.32	115	111.8	1.35	2.37
114.5	111.6	1.2	2.41	115.5	112.2	1.35	2.44

It will be seen that the results in this case are less consistent than in the previous case. This is due to a large extent, I think, to the fact that we were charging from the 110 V.D.C. dynamo, having ten large storage cells in series, and the voltage of the dynamo was fluctuating quite rapidly. It was impossible to read both ammeter and voltmeter at the same time, and between the times of reading the voltage would change. The method on discharge is more reliable than this unless a more constant charging source can be had.

CONCLUSION

A consideration of the above shows that any one or all of several methods may be used in determining the resistance of a blue cell. The method first considered in which the galvanometer was placed in shunt with a portion of the high resistance in series with the battery is a very simple and easy method of measuring the resistance, With

a little care fairly consistent results may be obtained. It is a method that I think may well be used as a laboratory experiment. The next method, the Condenser method, is also exceedingly simple. It has most of the good points of the previous method, and it eliminates some of the sources of error, e.g., In the condenser method no current is drawn from the cell except for a period of time just sufficient to charge and discharge the condenser. This prevents undue polarization. On the other hand, there is one point in which the former method has the advantage. The condenser method necessitates the reading of a ballistic throw of the galvanometer while the first method gives a steady deflection. The condenser method, however, seems to me to give the more consistent results.

The results obtained with Mance's Method compare favorably with those of either of the above methods. This, however, necessitates the closing of the circuit through a low resistance for a longer time, and if the cell is subject to polarization it is less commendable.

Lodge's Modification serves to render the galvanometer more sensitive to small changes of resistance since the galvanometer coil is always at its most sensitive position. The results obtained by this method are the most consistent I was able to obtain by any method. It has the disadvantage, however, of being more complicated than the condenser method. It also necessitates the closing of the circuit for a longer time and so is less desirable in case of a cell that polarizes rapidly.

Beetz's Method I think is not one that would prove advantageous in the laboratory. It gave only fairly consistent results under the most favorable circumstances, and in case of a cell that is at all variable, such as is likely to be measured in a laboratory, it did not prove at all satisfactory. I think then that for laboratory practice where gravity or similar cells are to be measured either of the following methods may be well employed.

1. Galvanometer as an ammeter.

2. The Condenser Method.

3. Mance's Method

4. Lodge's Modification of Mance's Method.

In the case of dry cells or other cells that polarize rapidly it seems to me that the condenser method is by far the most desirable, and is practically the only one of the above methods that is reliable.

In the case of storage cells either of the two methods, charging or discharging, explained above may be used with equal accuracy provided the charging source remains constant. Otherwise the method of discharging is much to be preferred.